

# Observation of $B^0 \rightarrow D^{*-} (5\pi)^+$ , $B^+ \rightarrow D^{*-} (4\pi)^{++}$ and $B^+ \rightarrow \bar{D}^{*0} (5\pi)^+$

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## Abstract

We report the first observation of a number of decay modes of the  $B$  meson, namely  $B^0 \rightarrow D^{*-} (5\pi)^+$ ,  $B^+ \rightarrow D^{*-} (4\pi)^{++}$  and  $B^+ \rightarrow \overline{D}^{*0} (5\pi)^+$ , where  $(n\pi)$  implies the combination of  $n$  charged pions. The analysis is based on a  $140 \text{ fb}^{-1}$  data sample collected at the  $\Upsilon(4S)$  resonance with the Belle detector at KEKB. We measure  $\mathcal{B}(B^0 \rightarrow D^{*-} (5\pi)^+) = (4.72 \pm 0.59 \pm 0.71) \times 10^{-3}$ ,  $\mathcal{B}(B^+ \rightarrow D^{*-} (4\pi)^{++}) = (2.56 \pm 0.26 \pm 0.33) \times 10^{-3}$  and  $\mathcal{B}(B^+ \rightarrow \overline{D}^{*0} (5\pi)^+) = (5.67 \pm 0.91 \pm 0.85) \times 10^{-3}$ . We also provide improved measurements of the branching fractions for the decay modes  $B^0 \rightarrow D^{*-} (3\pi)^+$ ,  $B^+ \rightarrow \overline{D}^{*0} (3\pi)^+$  and  $B^0 \rightarrow \overline{D}^{*0} (4\pi)^0$ .

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A large fraction ( $\sim 35\%$ ) of  $B$  meson decays is due to decay modes which are still unknown. While a sizable fraction of  $B$ 's decay into semileptonic final states ( $\sim 24\%$ ) [1], decays into hadronic final states are dominant. At present, however, only half of these final states correspond to measured exclusive hadronic decays.

On average,  $B$  mesons decay into a large number of particles: the mean charged particle multiplicity in hadronic  $B$  decay is measured to be  $5.8 \pm 0.1$  [2]. Decay products of  $D$  mesons make a significant contribution, but  $B$  decays to charmed states with a large number of accompanying pions,  $B \rightarrow \bar{D}^{(*)}(n\pi)$ , where the  $\pi$  are charged pions and  $n = 3, 4$ , are also known [3]. The invariant mass distribution of the multi-pion system, and the resonant decomposition for such decays, are important for the study of factorization [4].

In this paper, we present a study of inclusive  $B \rightarrow \bar{D}^{*0(-)}(n\pi)$  final states, where  $n = 3, 4$  and 5, and measure branching fractions for six decay modes. Inclusion of charge conjugate modes is implied throughout this paper.

The analysis is based on a  $140\text{ fb}^{-1}$  data sample at the  $\Upsilon(4S)$  resonance (10.58 GeV) and a  $16\text{ fb}^{-1}$  data sample 60 MeV below the  $\Upsilon(4S)$  peak (referred to as *off-resonance* data), collected by the Belle detector [5] at the asymmetric  $e^+e^-$  collider KEKB [6]. The data sample contains 152 million  $B\bar{B}$  events.

The Belle detector is a general purpose magnetic spectrometer with a 1.5 Tesla magnetic field provided by a superconducting solenoid. Charged particles are measured using a 50 layer Central Drift Chamber (CDC) and a 3 layer double sided Silicon Vertex Detector (SVD). Photons are detected in an electromagnetic calorimeter (ECL) consisting of 8736 CsI(Tl) crystals. Exploiting the information acquired from an array of 128 time-of-flight counters (TOF), an array of 1188 silica aerogel Čerenkov threshold counters (ACC) and  $dE/dx$ -measurements in CDC we derive particle identification likelihoods  $\mathcal{L}_{\pi/K}$ . A kaon candidate is identified by a requirement on the likelihood ratio  $\mathcal{L}_K/(\mathcal{L}_K + \mathcal{L}_\pi)$  such that the average kaon identification efficiency is  $\sim 90\%$  and the pion fake rate is  $\sim 9\%$ . Similarly charged pions are selected with an efficiency of  $\sim 91\%$  and the kaon fake rate is  $\sim 10\%$ . We select charged pions and kaons that originate from the region  $|\Delta r| < 0.2\text{ cm}$  and  $|\Delta z| < 4\text{ cm}$  with respect to the run dependent interaction point, where  $\Delta r$ ,  $\Delta z$  are the distances of closest approach of  $\pi/K$  tracks to the interaction vertex in the plane perpendicular to the beam axis and along the beam axis, respectively. All tracks compatible with the electron hypothesis ( $\sim 0.2\%$  fake rates from pion/kaon) are eliminated. No attempt has been made to identify muons, which represent a background of about 2.7% to the pion tracks. Candidate  $\pi^0$  mesons are identified as a pair of isolated ECL clusters with invariant mass in the window  $118\text{ MeV}/c^2 < M_{\gamma\gamma} < 150\text{ MeV}/c^2$ . The energy of each photon is required to be greater than 30 MeV in the barrel region, defined as  $32^\circ < \theta_\gamma < 128^\circ$ , and greater than 50 MeV in the endcap regions, defined as  $17^\circ < \theta_\gamma \leq 32^\circ$  or  $128^\circ < \theta_\gamma \leq 150^\circ$ , where  $\theta_\gamma$  denotes the polar angle of the photon with respect to the direction opposite to the  $e^+$  beam. A mass constrained fit is applied to obtain the 4-momenta of  $\pi^0$ 's.

Beam gas events are rejected using the requirements  $|P_z| < 2\text{ GeV}/c$  and  $0.5 < E_{\text{vis}}/\sqrt{s} < 1.25$ , in the  $\Upsilon(4S)$  rest frame, where  $P_z$  and  $E_{\text{vis}}$  are the sum of the longitudinal momentum and the energy of all reconstructed particles, respectively, and  $\sqrt{s}$  is the sum of the beam energies in the  $\Upsilon(4S)$  rest frame.

The  $\bar{D}^0$  meson is reconstructed through its decay to  $K^+\pi^-$ . A vertex constrained fit is performed and the invariant mass is required to be within  $17\text{ MeV}/c^2$  ( $\sim 3.5\sigma$ ) of the nominal  $D$  mass.  $D^{*-}$ 's are then reconstructed by combining the  $\bar{D}^0$  with a slow charged pion with  $|\Delta r| < 2.0\text{ cm}$  and  $|\Delta z| < 10.0\text{ cm}$  with respect to the  $D$  vertex ( $D$  vertex resolutions are  $\sigma_r \sim 0.026\text{ cm}$  and  $\sigma_z \sim 0.016\text{ cm}$ ). The signals of  $B \rightarrow \bar{D}^{*0}(n\pi)$  are reconstructed through the decay chain  $\bar{D}^{*0} \rightarrow \bar{D}^0\pi^0$ . Candidate

$D^{*-}(\overline{D}^{*0})$  are selected when the reconstructed mass difference between  $\overline{D}^*$  and  $\overline{D}^0$  is within 2.0 (2.4) MeV/ $c^2$  of the nominal mass difference  $\Delta M$ , which corresponds to  $\sim 3.5$  (3.0)  $\sigma$  resolution on  $\Delta M$ . A kinematic fit with the nominal  $\overline{D}^*$  mass is applied to obtain the 4-momenta of the  $\overline{D}^*$  candidate.

The  $\overline{D}^*$  candidate is then combined with  $n$  pions to reconstruct the  $B$  meson. All  $n$  pions are required to satisfy  $|\Delta r| < 0.2$  cm and  $|\Delta z| < 0.8$  cm with respect to the  $\overline{D}$  vertex. Continuum ( $e^+e^- \rightarrow q\overline{q}$ , where  $q = u, d, s, c$ ) events are suppressed with the criterion,  $|\cos\theta_{\text{thrust}}| < 0.8$ , where  $\theta_{\text{thrust}}$  is the angle between the thrust axis of the  $B$  candidate daughters and the thrust axis of the remaining tracks and isolated ECL clusters.

The signal can then be identified by two kinematic variables calculated in the  $\Upsilon(4S)$  rest frame. The first is the energy difference,  $\Delta E = E_{D^*} + \sum_{i=1}^n E_{\pi_i} - E_{\text{beam}}$ , where  $E_{D^*}$  is the energy of the  $\overline{D}^*$  candidate,  $E_{\pi_i}$  is the energy of the  $i$ th pion in the  $n\pi$  system and  $E_{\text{beam}} = \sqrt{s}/2$  (Fig. 1). The second variable is the beam-energy constrained mass,  $M_{\text{bc}} = \sqrt{E_{\text{beam}}^2 - |\vec{P}_{D^*} + \sum_{i=1}^n \vec{P}_{\pi_i}|^2}$ , where  $\vec{P}_{D^*}$  and  $\vec{P}_{\pi_i}$  are momentum vectors of the  $\overline{D}^*$  candidate, and the  $i$ th pion in the  $n\pi$  system. Typical resolutions for these variables are 8.5 MeV and 2.7 MeV/ $c^2$ , respectively. In the extraction of the signal yield, we require  $5.273 \text{ GeV}/c^2 < M_{\text{bc}} < 5.288 \text{ GeV}/c^2$  and  $M_{\text{bc}} > 5.27 \text{ GeV}/c^2$  for  $D^{*-}(n\pi)$  and  $\overline{D}^{*0}(n\pi)$ , respectively, and we fit the  $\Delta E$  distribution from  $-150$  MeV to  $150$  MeV. In many  $B$  decay analyses, the  $\Delta E$  distribution includes peaks or other structures due to related  $B$  decays with an additional particle, one particle less than in the mode under study or misidentification of a particle from a topologically similar decay mode. In this case, we do not observe such structures within our fitting range. We do not use the  $M_{\text{bc}}$  distribution to obtain signal yields, because peaking backgrounds in that distribution cannot be distinguished from signal. Selected events contain multiple  $B$  candidates with a multiplicity depending on the signal channels, which varies from 1.2 to 1.8. For each event we choose a unique  $B$  candidate, taking the combination resulting in the minimum value of  $((M_{\text{bc}} - M_B)/\sigma_{M_{\text{bc}}})^2 + (\Delta M_D/\sigma_{M_D})^2 + (\Delta M_{D^*}/\sigma_{M_{D^*}})^2$ .

We have studied continuum events and other  $B$  decays as possible sources of background. Background due to continuum events is studied by analysing the  $16 \text{ fb}^{-1}$  off-resonance data and there we do not find any peak near  $\Delta E = 0$ .

$B$  decays (both signal and background) are studied with Monte Carlo (MC) event samples. MC events are generated using the  $QQ$  event generator [7] with a phase space distribution for the  $n\pi$  system, and the response of the Belle detector is simulated by a GEANT3-based program [8]. The simulated events are then reconstructed and analysed with the same procedure as is used for the real data.

We have investigated the possibility of reconstructing  $B \rightarrow \overline{D}^{*- (0)}(n'\pi)(m\pi^0)$  channels as  $D^{*- (0)}(n\pi)$  due to the loss and/or addition of pions, where  $n = 3, 4$  or  $5$ ,  $n' = n, n \pm 1$  and  $m = 0$  or  $1$  and here we observe a linear background without any structure around  $\Delta E = 0$ . We have also studied  $B \rightarrow \overline{D}^{*0}(\rightarrow \overline{D}^0\gamma)(n\pi)$  MC events reconstructed as  $B \rightarrow \overline{D}^{*0}(\rightarrow \overline{D}^0\pi^0)(n\pi)$  and  $D^{*- (0)}(n\pi)$  events reconstructed as  $D^{*0(-)}(n\pi)$ . In each case, we find a  $\Delta E$  distribution peaked at zero, but with a larger width than the corresponding signal distribution. We also consider backgrounds due to  $B \rightarrow \overline{D}^0(n\pi)$  and  $B \rightarrow \overline{D}^0(n\pi)\pi^0$  with  $n \geq 4$ . Such decays have not yet been observed; assuming branching fractions equal to those of the corresponding  $B \rightarrow \overline{D}^{*0}(n\pi)$  and  $B \rightarrow \overline{D}^{*0}((n+1)\pi)$  modes, respectively, we find a small background to  $D^{*-}(n\pi)$  for  $n = 3, 4$ , and a negligible contribution to the other final states. Finally, we fit MC signal distributions without and with contributions from the various feed-across backgrounds. The ratio of those two signal yields ( $F_r$ ) depends on the signal channels and varies from 0.99 to 0.87. Observed signal yields are corrected with the corresponding  $F_r$  when extracting branching fractions.

We have studied the following six  $B$  decay modes:  $B^0 \rightarrow D^{*-}(3\pi)^+$ ,  $B^+ \rightarrow \overline{D}^{*0}(3\pi)^+$ ,  $B^+ \rightarrow D^{*-}(4\pi)^{++}$ ,  $B^0 \rightarrow \overline{D}^{*0}(4\pi)^0$ ,  $B^0 \rightarrow D^{*-}(5\pi)^+$  and  $B^+ \rightarrow \overline{D}^{*0}(5\pi)^+$ . Figure 1 shows the  $\Delta E$  distributions for these decay modes. Statistically significant structures near  $\Delta E = 0$  are observed. We have also checked the corresponding  $\Delta E$  distributions for events in the  $M_{bc}$  sideband region ( $5.23 \text{ GeV}/c^2 < M_{bc} < 5.26 \text{ GeV}/c^2$ ): no structure is observed. For all the decay modes under study, backgrounds are fitted with a linear function. The signal shape is modelled with a sum of two Gaussian distributions for  $B \rightarrow \overline{D}^{*-}(n\pi)$ . The  $\overline{D}^{*0}(n\pi)$  signal is fitted with a sum of the Crystal Ball lineshape (CB) [9],

$$F(\Delta E) = A \cdot \exp \left( -0.5 \cdot \left( \frac{\Delta E}{\sigma_{\Delta E}} \right)^2 \right) \quad \text{for } \Delta E \geq -\alpha \sigma_{\Delta E}$$

$$= A \cdot \exp \left( -0.5 \cdot \alpha^2 \right) \cdot \left[ 1 - \frac{\alpha}{n} \cdot \frac{\Delta E}{\sigma_{\Delta E}} - \frac{\alpha^2}{n} \right]^{-n} \quad \text{for } \Delta E < -\alpha \sigma_{\Delta E}$$

and a Gaussian. The  $n$  and  $\alpha$  parameters of the CB and the fractional area of the second Gaussian are fixed from fits to the MC sample. Signal yields obtained from the fit are summarised in Table I.

TABLE I: Measured signal yields and branching fractions.

Channel	Signal yield			$\mathcal{B} \times 10^3$				
$B^0 \rightarrow D^{*-}(3\pi)^+$	2554.9	$\pm$	58.4	6.81	$\pm$	0.23	$\pm$	0.72
$B^+ \rightarrow D^{*-}(4\pi)^{++}$	445.9	$\pm$	31.7	2.56	$\pm$	0.26	$\pm$	0.33
$B^0 \rightarrow D^{*-}(5\pi)^+$	449.6	$\pm$	32.0	4.72	$\pm$	0.59	$\pm$	0.71
$B^+ \rightarrow \overline{D}^{*0}(3\pi)^+$	1728.4	$\pm$	52.9	10.55	$\pm$	0.47	$\pm$	1.29
$B^0 \rightarrow \overline{D}^{*0}(4\pi)^0$	280.6	$\pm$	36.5	2.60	$\pm$	0.47	$\pm$	0.37
$B^+ \rightarrow \overline{D}^{*0}(5\pi)^+$	341.2	$\pm$	40.6	5.67	$\pm$	0.91	$\pm$	0.85

The signal efficiency depends on the invariant mass ( $M_{n\pi}$ ) of the  $n\pi$  system. Signal efficiencies are calculated from MC event samples in  $100 \text{ MeV}/c^2$  bins of  $M_{n\pi}$ .

In order to obtain the signal yield in each  $M_{n\pi}$  bin, we perform a fit to  $\Delta E$  distributions in each bin to avoid the possible uncertainty due to different background shapes in signal and sideband regions of  $M_{bc}$ . Efficiency corrected  $M_{n\pi}$  spectra are shown in Fig. 2. Invariant mass distributions of the  $3\pi$  system ( $M_{(3\pi)}$ ) in  $B \rightarrow \overline{D}^*(3\pi)$  decays show clear evidence for the presence of  $a_1$  (Fig. 2(a,d)). The  $M_{4\pi}$  distributions in Fig. 2(b,e) do not show any resonant structure.  $M_{5\pi}$  distributions in Fig. 2(c,f) show a peak around  $2 \text{ GeV}/c^2$  which, however, does not correspond to any known resonance. We also search for narrow resonances in the  $M_{5\pi}$  distributions, after the subtraction of  $\Delta E$  sidebands. Apart from a peak due to the  $D_s^+$ , no narrow structure is observed.

Inclusive branching fractions obtained for the six modes are listed in Table I, where the first error is statistical and the second error is systematic. This is the first measurement of the branching fractions of  $B^+ \rightarrow D^{*-}(4\pi)^{++}$ ,  $B^0 \rightarrow D^{*-}(5\pi)^+$  and  $B^+ \rightarrow \overline{D}^{*0}(5\pi)^+$ . The branching fractions for the decay modes  $B^0 \rightarrow D^{*-}(3\pi)^+$ ,  $B^+ \rightarrow \overline{D}^{*0}(3\pi)^+$  and  $B^0 \rightarrow \overline{D}^{*0}(4\pi)^0$  are measured with better precision than in previous studies [1]. We do not exclude contributions from exclusive channels  $B \rightarrow \overline{D}^* D_s^+$ ,

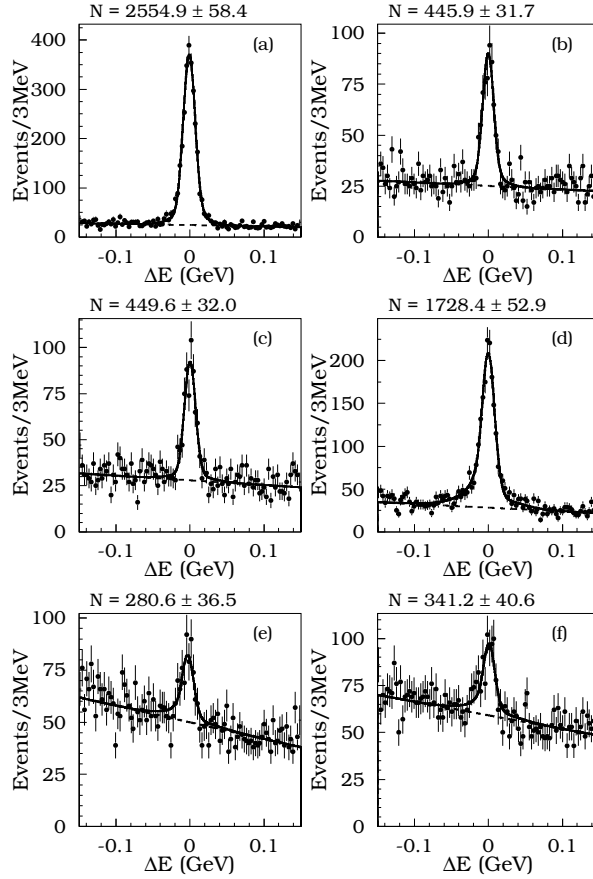


FIG. 1:  $\Delta E$  distributions for six  $\overline{D}^*(n\pi)$  combinations: (a)  $B^0 \rightarrow D^{*-}(3\pi)^+$ , (b)  $B^+ \rightarrow D^{*-}(4\pi)^{++}$ , (c)  $B^0 \rightarrow D^{*-}(5\pi)^+$ , (d)  $B^+ \rightarrow \overline{D}^{*0}(3\pi)^+$ , (e)  $B^0 \rightarrow \overline{D}^{*0}(4\pi)^0$  and (f)  $B^+ \rightarrow \overline{D}^{*0}(5\pi)^+$ . Points with error bars are the observed events in data, solid lines are the results from the fit and dashed lines represent the background components.

$B \rightarrow \overline{D}^* D^{*+}$ ,  $B \rightarrow \overline{D}^* D^+$ ,  $B \rightarrow \overline{D}^* D^{*+} K_S$  etc. The largest contributions of this type to inclusive  $\overline{D}^*(3\pi)$  and  $\overline{D}^*(5\pi)$  are expected to come from  $\overline{D}^* D_s^+$ , with  $D_s^+ \rightarrow (3\pi)^+$  ( $\mathcal{B} = 1.01 \pm 0.28\%$  [1]) and  $D_s^+ \rightarrow (5\pi)^+$  ( $\mathcal{B} = 0.65 \pm 0.18\%$  [1]), respectively. We conduct a search for these modes by fitting invariant mass distributions of  $n\pi$ ,  $M_{n\pi}$  for signal events ( $|\Delta E| < 30$  MeV) and find yields of  $27.8 \pm 7.7$ ,  $15.6 \pm 5.4$ ,  $8.4 \pm 3.9$  and  $11.3 \pm 5.4$  in  $B^0 \rightarrow D^{*-}(3\pi)^+$ ,  $B^+ \rightarrow \overline{D}^{*0}(3\pi)^+$ ,  $B^0 \rightarrow D^{*-}(5\pi)^+$  and  $B^+ \rightarrow \overline{D}^{*0}(5\pi)^+$  channels, respectively. Within the statistical errors, these results are consistent with PDG expectations. The expected contribution from other modes are smaller than  $B \rightarrow \overline{D}^* D_s^+$  by a factor  $\sim 4$ .

The systematic uncertainty is obtained from a quadratic sum of nine terms, which are shown in Table II: the uncertainty in (a) the track finding efficiency, ranging from 1% for high momentum tracks to 8% for 80 MeV/c pions, calculated from partially reconstructed  $D^{*-} \rightarrow \overline{D}^0(\rightarrow K_s^0(\rightarrow \pi^+\pi^-)\pi^+\pi^-)\pi^-$  events and a track embedding study; (b) the slow  $\pi^0$  finding efficiency; (c)  $K/\pi$  selection efficiencies (PID), calculated using  $D^{*-} \rightarrow \overline{D}^0(\rightarrow K^+\pi^-)\pi^-$  events; (d) branching fractions of  $D^{*-}(\overline{D}^{*0}) \rightarrow \overline{D}^0\pi^{-(0)}$ ,  $\overline{D}^0 \rightarrow K^+\pi^-$  and  $\pi^0 \rightarrow \gamma\gamma$ ; (e) the uncertainty in the feed-across from other

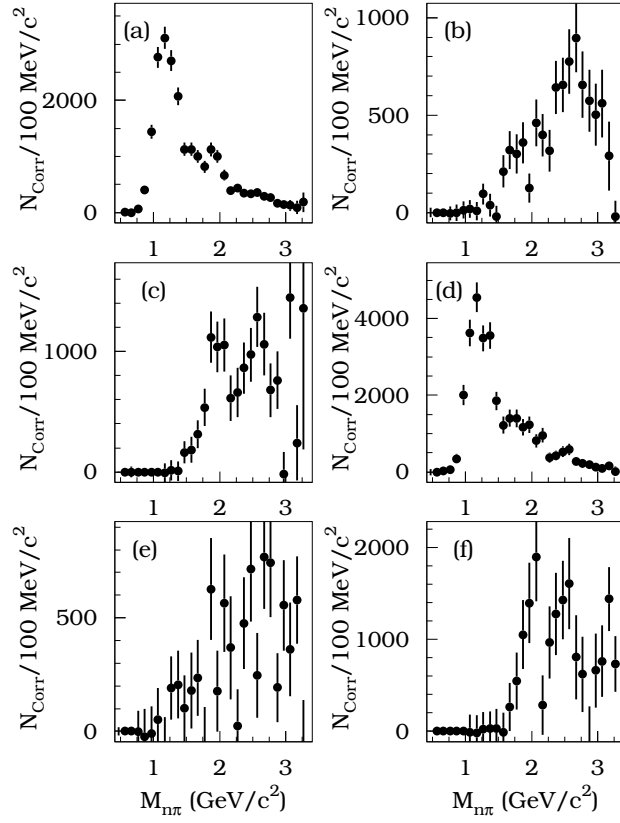


FIG. 2: Efficiency corrected  $n\pi$  invariant mass spectra for (a)  $B^0 \rightarrow D^{*-} (3\pi)^+$ , (b)  $B^+ \rightarrow D^{*-} (4\pi)^{++}$ , (c)  $B^0 \rightarrow D^{*-} (5\pi)^+$ , (d)  $B^+ \rightarrow \bar{D}^{*0} (3\pi)^+$ , (e)  $B^0 \rightarrow \bar{D}^{*0} (4\pi)^0$  and (f)  $B^+ \rightarrow \bar{D}^{*0} (5\pi)^+$ .

TABLE II: Contributions of systematic uncertainties (in %).

	$D^{*-}$			$\bar{D}^{*0}$		
	$3\pi$	$4\pi$	$5\pi$	$3\pi$	$4\pi$	$5\pi$
Track finding	8.7	11.0	12.7	5.4	6.6	7.9
Slow $\pi^0$	-	-	-	7.0	7.0	7.0
PID	4.9	5.0	4.8	5.0	5.2	5.3
Branchings	2.5	2.5	2.5	5.3	5.3	5.3
Feed-across	0.8	1.0	2.0	0.9	1.4	2.2
Fitting	0.5	1.2	1.4	2.4	4.0	5.5
Selection	2.5	3.7	4.9	3.3	5.7	4.7
MC	0.8	0.8	2.2	1.2	1.1	1.7
$N_{B\bar{B}}$	0.5	0.5	0.5	0.5	0.5	0.5
Total	10.6	13.0	15.0	12.3	14.1	15.0

decay modes which is calculated by changing the relative branching fractions of backgrounds to signal by one sigma of their errors; (f) the uncertainties due to the choice of signal shape and histogram binning.  $\Delta E$  distributions are also fitted with (i) single Gaussian (CB), (ii) modified Gaussian (CB), where Gaussian power has changed from 2 to 1.4, (iii) asymmetric Gaussian, (iv) modified Gaussian (CB) + Gaussian and (v) asymmetric Gaussian + Gaussian for  $D^{*-}(n\pi)$  ( $\overline{D}^{*0}(n\pi)$ ) signals. Ratio of fitted yields in data and MC signals are calculated for these functions and the variation of these ratio is taken as the systematic error due to fitting function; (g) the uncertainties due to selection criteria, which are calculated by varying those criteria by one sigma of their errors, (h) limited MC statistics and (i) the uncertainty in the total number of  $B\overline{B}$  events ( $N_{B\overline{B}}$ ).

In summary, we have made first observations of decay channels  $B^0 \rightarrow D^{*-}(5\pi)^+$ ,  $B^+ \rightarrow D^{*-}(4\pi)^{++}$  and  $B^+ \rightarrow \overline{D}^{*0}(5\pi)^+$  using 152 million  $B\overline{B}$  events. We measure inclusive branching fractions for these three decay modes. We have also made precise measurements of the branching fractions for the decay channels  $B^0 \rightarrow D^{*-}(3\pi)^+$ ,  $B^+ \rightarrow \overline{D}^{*0}(3\pi)^+$  and  $B^0 \rightarrow \overline{D}^{*0}(4\pi)^0$ .

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